Systems and avionics

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1.0 WHAT ARE THE CHALLENGES?

1.1 Scope

This paper looks to future developments and concepts in Systems and Avionics. One hundred years ago neither 'avionics' nor even 'systems' would have been recognised as having a place in aeronautics. The concept of aircraft systems developed, as the complexity of each element of the aircraft grew, requiring specialism in the design, operation and maintenance of those elements. Early examples would have been the propulsion and flying controls systems. By the 1930s passenger aircraft might have carried, in addition to the pilots, a navigator, flight engineer and radio operator, each responsible for his own collection of systems, with the aircraft itself probably having an embryonic electrical system.

Parallel developments in the fields of instrumentation, motion sensing and servo control, offered the means to perform many of the functions of the new systems automatically. The availability of semi conductor and computing devices accelerated the process, thus relieving the crew of more mundane tasks and reducing the crew complement to yield more capacity for carriage of people, freight or weaponry.

This process continues as products and techniques, often initially developed to support the entertainment, personal computing, automotive and other mass consumer needs, become available for development and adaptation to the needs of aeronautics. Future developments and progress in this field are dependent on:

- The identification of the requirement in the aircraft and hence at system level.
- The availability of new ideas and products from the broader, mainly electronics based industries.
- The continuing cross fertilisation of knowledge and capability between the civil and military sectors.

1.2 The widening horizons

The Wright brothers' tasks were to achieve sufficient lift, a light rigid structure, a light propulsion unit and most difficult perhaps of all, adequate controllability and manoeuvrability. Once their vehicle climbed into the air and stayed there a whole expanding range of challenges arose over time:

- Navigating from place to place and weapon delivery.
- Communicating with the ground and other aircraft.
- Predicting and avoiding the weather en route.
- Blind flying.
- Avoiding other traffic and obstacles in the air and on the ground.
- Taking off and landing, or finding targets, in all weathers.
- Interacting with all the users in an air traffic control system or battle space.
- Protecting against exceeding the safe flight envelope. Increasing military and battle capabilities.
- Providing growing entertainment, work facilities and comfort on board.

Most of these seem obvious today. However, in 1903 many would have seemed to belong to the realms of fantasy. Certainly there would have been little belief that the means of satisfying those needs would have become available within a lifetime. So how are the requirements for future systems and avionics and the solutions to be identified? Perhaps the starting points should be the commercial and military pressures, and even the whims of the users, supported by a faith in the future emergence of ever more powerful and inventive sensors, computers and equipment.

1.3 The challenges

The aspirations of the broad community of aircraft users can usefully be grouped under the four headings of safety, cost, effectiveness and environmental impact.

1.3.1 Safety

With the continuing growth of aviation the public perception of a safe system must be retained, which means a reduction in the number of accidents for both civil and military aircraft. The growing complexity of the machine combined with the delegation of routine control to the aircraft and ground systems means that the way in which flight and maintenance crews interact with these, needs constant re-examination. The study and application of human factors needs to be advanced to enable more effective inter-communication. The number of 'messages', whether visible, aural, tactile or whatever, will need to be simplified and better structured. The recent use of commercial aircraft as terrorist weapons has brought new attention to the objective of protecting the whole air transport system from misuse.

1.3.2 Cost

As well as minimising the cost of manufacturing an aircraft, the operational and training costs of flight and maintenance crews must be reduced. More advanced flight management and air traffic management systems will offer more efficient use of the air space and better runway utilisation to reduce en route and landing costs.

1.3.3 Effectiveness

In the commercial world there continues to be the demand to provide, economically, more passenger space with better in-flight services, air quality, catering, frequency, punctuality and speed. In the military field the demand for greater lethality, self protection and even invulnerability, grows. In both fields reliability and availability are vital and the need to improve fault diagnosis and rectification, maintenance and condition monitoring system performance are endemic.

1.3.4 Environmental impact

The ability to reduce drag and improve engine efficiency and hence reduce emissions and noise by operating in less stable regimes or by more flexible lift surfaces, requires the availability of suitable control systems. Avionic systems, offering more flexibility of control for aircraft in the en route and terminal areas, are needed to reduce the impacts on the environment and centres of population.

2.0 MEETING THE CHALLENGES

This section discusses in more detail the potential means by which the challenges for the next century, referred to in paragraph 1.3 above, are likely to be achieved. Many of the various changes discussed have an effect on most of the challenge areas reviewed below.

2.1 Safety and security

For civil aviation, safety will continue to be the major priority. It will be essential, not only to ensure that the technology changes made to future aircraft do not increase the accident rate, but actually reduce this rate since, with the increasing number of aircraft movements, the number of accidents to civil aircraft would become unacceptably large.

For military aircraft operating in training, peace-keeping and other non wartime situations, similar considerations will apply, since there will be an ever increasing unwillingness, by the public, to accept the loss or capture of military crews.

At the start of this century, security issues have, understandably, been given a major priority. Complex, normally covert, monitoring systems will be developed to detect and deter potential terrorists and 'hijackers'. It is to be hoped that with these measures in place and, linked with a return to a less violent society, security will not be a major issue during the later part of the century.

All the potential changes and developments discussed will have an impact upon safety, but there are particular developments which will play a major role. These may well include, but not be limited to:

2.1.1 Synthetic vision

As described in more detail later, these systems use data from a range of sensors to provide a flight crew with a pictorial representation of the outside world, even in bad weather. They will provide major improvements in the safety during the en route, approach and landings phases of flight and during pre and post flight manoeuvring. The performance improvements from use of such systems, combined with decreased weight, size and cost will also make them cost effective in both civil and military applications. Additional operational advantages will be available from the use of such systems.

2.1.2 Air traffic management (ATM)

In order to meet the increasing demands for air space, traffic densities will increase, particularly in the proximity of airports. The traffic capacity of air traffic management systems will need to be continuously increased while simultaneously continuing to reduce the possibility of in flight collisions to a very low level. Such improvements will require major innovations both in the airborne and ground equipment with reliable data links between the ground and other aircraft.

On military aircraft, in peacetime, these systems will also be very relevant since the increase in civil flights will impinge upon the availability of 'military only' airspace and military aircraft will increasingly be flying in civil controlled airspace.

2.1.3 Human factor issues

Until recently, designs and procedures have been developed which have not taken full account of the human factor issues on the flight deck, in the air traffic control centre and during maintenance, which can lead to errors and misunderstanding. There is a wealth of evidence that the lack of consideration of these issues has been a major element in many accidents and incidents. The increasing complexity of aircraft systems will mean that much more attention will have to be given to these issues during the design, operation and maintenance of future aircraft systems.

2.1.4 Monitoring systems

There will be major increases in the use of and reliance upon, 'Health' and 'Usage' systems and equipment on both civil and military aircraft. These systems will have the capability of monitoring not only mechanical and electrical components, but also the flight situation of the aircraft, taking collision, atmospheric and hostile threats into account. Alerts of actual or pending failures or hazards will be raised and operating and maintenance personnel will be provided with guidance on how to remedy the situation.

2.1.5 Use of uninhabited airborne vehicles (UAVs)

While cogent arguments can be made that safety in flight can be improved by removing the flight crew and relying entirely on automated processes, controlled and monitored from the ground, it seems improbable that this will happen on commercial passenger-carrying flights, even in the next century. A presence on the flight deck is likely to continue unless it can be shown that the automated devices can be programmed to provide the same breadth of response as the human brain, under all normal and non-normal conditions.

For military combat and reconnaissance aircraft however this is not the case, and safety will be increased, both for peace and war time operations, and costs reduced, by a marked increase in the use of unoccupied vehicles in these roles.

The same safety advantages will apply for civil registered uninhabited vehicles carrying out surveillance work or, for example, providing television coverage of sporting and other events from the air.

2.1.6 Certification procedures

With the increases in system complexities, inter-reactions & inter-dependencies and redundancy & reconfiguration capabilities, the certification processes will have to face major changes. The use of integrated modular avionic systems (IMA) and increased flexibility and optimisation of power supplies will increase and expand. It is foreseen that the certification processes will have to become totally integrated and concurrent with the design of the systems, while still maintaining the requisite high standards of system and equipment integrity and independence.

2.2 Cost of ownership

The pressure to reduce both initial and in-service costs will continue for both civil and military aircraft. Many of the safety issues discussed in paragraph 2.1 above also provide potential cost savings. However with the ever increasing pressure of liability issues, the industry, at all levels, will have to decide whether it can afford not to accept the costs inevitably associated with some safety improvements.
The main drivers for cost reduction are envisaged to be:

2.2.1 Fuel

Engine efficiencies will increase with associated reduction in fuel consumption. This will involve further optimisation of the electronic engine control systems which, for civil aircraft in particular, will be further integrated with more advanced flight management systems to assist in operation at the most fuel efficient altitudes and speeds.

2.2.2 System design

The integration of systems and flexibility of power supplies, discussed under the Certification Procedures in paragraph 2.1.6 above, has major potential for cost savings. While the initial design and certification costs may be higher, the reductions in weight will provide major savings in fuel costs. The operational practices and maintenance procedures for such systems will be optimised, the need for *en route* spares provisioning reduced and the training procedures for both flight crew and maintenance staff improved.

2.2.3 Air traffic management (ATM) and flight/mission management

For civil aircraft, the more efficient use of the air space will provide reductions in flying time and increased runway usage and reduce en route and landing costs. For military aircraft, the improvements in mission systems will improve the efficiency of the mission and help to reduce costs by increasing effectivity and reducing losses.

2.2.4 Synthetic vision and human factors

The cost advantages to be obtained regarding both safety of flight and improving the efficiency of the man-machine interfaces, both in the air and on the ground, will be considerable.

2.2.5 Uninhabited airborne vehicles (UAVs)

For military aircraft the cost savings relative to reduced initial and replacement costs of the vehicle, lower operating costs and reduced crew training will be considerable. For civil UAVs the savings on initial and operating costs for such vehicles, relative to using more conventional aircraft, such as rotorcraft, will also be large.

2.2.6 Obsolescence of electronic systems

The structural and mechanical components of contemporary aircraft enjoy remarkably long lives, in the order of thirty years and more. It can be expected that future aircraft will improve in this regard. The obsolescence cycle for the electronic components is typically less than five years. The cost of supporting avionic devices which contain components more than five years old will eventually exceed the first cost of the device by an order of magnitude or more. Also, while it may be perfectly acceptable to operate a sound fuselage for thirty years, it is unlikely that avionic devices of this age will have the computing and interface capacities to accommodate the systems changes that will be needed to support operations over such a period. Thus the future must contemplate some method where the cost of regular upgrades is factored into the acquisition and operation of the aircraft.

2.3 Effectiveness

Meeting the 'customer's needs' is vital for the future of the aerospace industry. Avionic systems, in particular, will have a major role to play to meet the insatiable demands of both the military and civil markets. While satisfying the increased performance objectives, both will require high standards of availability and reliability, while keeping the initial and in-service costs to a minimum. The basic design concepts for the aircraft will be such that performance up-grades to the avionics systems are possible during the in-service life of the aircraft, without the need for expensive and time consuming re-design and re-certification.

2.3.1 Military capability

For the military aircraft the primary role is to complete its mission successfully.

For both manned and unmanned vehicles, improved navigation capability will be based upon live satellite information and stored data which will have very high accuracy and reliability. The systems will provide very accurate three-dimensional data with enhanced terrain data available when needed. Improved 'over the horizon' radar and other counter measures will be available to reduce vulnerability to surprise attack. To take account of the overall 'Battle Space' situation, cockpits, whether in the aircraft, or at the ground based control centre, will use enhanced vision systems and three dimensional head-up displays with data and communication links to other appropriate information. The provision of the necessary data directly to the pilot, using helmets or more direct means, will increase.

2.3.2 Civil capability

For the civil air transportation system the emphasis will continue to be on availability, reliability and punctuality. These will have to be achieved while satisfying the demand for increased passenger entertainment, catering and business services, improved air quality and more passenger space. Reductions in flight times resultant from increase in speed will also be available. Advantage will be taken of the improvements in navigation and communication capabilities derived from military developments. Cockpit displays will also become increasingly more sophisticated taking account of the military developments and be based upon sound man-machine interface principles. The availability and reliability of passenger services will be improved by using fault finding and maintenance techniques based upon the detailed analysis carried out as part of the original design programme. Cabin air systems will be improved by using advanced sensing systems to monitor the air quality across the whole of the cabin.

2.4 Environmental impact

International pressure to reduce emissions, noise and upper atmosphere pollution will increase. With current engine technology the most effective way to reduce these emissions is to improve engine efficiency which will require more sophistication in the electronic control systems and associated sensors.

Improved ATM systems will reduce flight times and optimise approach and landing paths, thus reducing both emissions and the impact of noise in the airport locations.

Changes to the physical shape of the aircraft, both to reduce drag and trans-sonic shock patterns will only be practical if the control and stability needs of the aircraft can still be met. This will be achieved by the design and development of more complex and reliable flight control systems with the provision of increased redundancy to ensure full control capability at all times during the flight.

With the increasing requirements for electrical power in the aircraft, the development of solar power sources and regenerative production of electrical power have the potential to produce significant fuel savings with a corresponding reduction in emissions.

The viability of more radical changes to propulsion system design and the change from non-renewable sources of fuel will be dependant not only on the ability to store and handle such fuels, but also upon the control systems used to produce and control the thrust available from these future engines.

3.0 SYSTEM DEVELOPMENTS

Many of the ways we do things today are governed by past history, whether by mere precedent and a necessary degree of conservatism or because we have a group of users who have been trained to do things in a particular way, making it uneconomical to engage in rapid and wholesale change. The pace of adoption of many of the advances described below will be governed by these restrictions rather than by the availability of the technology.

3.1 The man machine interface

A frequent complaint about today's systems is the user's difficulty of absorbing exactly what the system is doing, particularly in unusual situations. Most of the advances in systems will bring more rather than less functionality. To make these new systems more easily usable, much of the system function will have to be carried out automatically with the lower level decisions delegated to the systems themselves. This will allow the human interfaces to be simplified for the flight, operations, maintenance and air traffic control users. This implies a wholesale review of what should be controllable by the crew, what should be controlled by the system, how much information is displayed continuously and how much information should be volunteered or placed on display at a time determined by the system.

The main source of information to the user is currently through visual displays. In order to spread the information load, both audible and tactile feedback from the systems will be used. Audible plain English messages from the aircraft's systems will become commonplace. Force or other feedback through control levers and knobs will indicate to the user that he is driving towards a limitation, particularly where a pilot needs to multi task or be head up in a combat aircraft. As systems become fully automatic, means to maintain the necessary human attention will have to be provided by monitoring and, where needed, stimulating the operator.

The basic 'T' of instruments was a way of ensuring good user habits, spreading good design practice and ensuring that training and learning was transferable from one aircraft to another. Future aircraft will use re-configurable displays such as cathode ray tubes, liquid crystal displays or their successors. The access to the system functions required for a whole range of transport aircraft will become standardised as a standard group of 'pages'. The content of each page and the links between pages will be the same across a wide range of aircraft. The users will make selections by 'point and click' in what will then be seen as a time honoured fashion. In combat aircraft the rapid tempo of operation means that multiple ways of selection will be used such as context sensitive speech inputs linked to the 'page' on display and the use of helmet mounted systems to point to and designate a selection. The flight control systems will minimise the differences in feel and handling between such aircraft and the single qualification of users to operate a wide range of aircraft from more than one manufacturer will become a reality. The savings in training costs will be enormous.

These advances imply that transport aircraft at least will become easier to operate, making the prospect of hijack or other misappropriation more likely. This will be countered by systems using scanning of fingerprints, cornea or other biometric data to enable access. The checks are likely to be repeated throughout the period of operation and the checks must therefore be non-intrusive. The checking software will be in non volatile memory to prevent tampering. These check processes will be applied to the operators of the air traffic control system and to maintenance and loading staff as well as to flight crews.

The growing functional complexity of the aircraft will mean that maintenance engineers will not be able to have the range of detailed knowledge needed to fix problems during a short turn round. Systems with redundant sensors and controllers will reduce the occurrence of maintenance actions further reducing the experience base. Maintenance staff will be provided with a headset mounted display that will give access to the aircraft's prior history, a trouble shooting guide and access to lessons learned by other maintainers of similar systems. The same system will record each maintenance action as it occurs, giving a traceable record.

There will be a major change in the working environment for air traffic controllers. Ground based computers will agree the basic flight plan strategies, exchanging information by data link with aircraft. Short term de-confliction will be handled by the aircraft themselves. The controller will be elevated to the position of system manager and strategist with the ground system referring major decisions up to the controller for confirmation. Voice communication will be reserved to the handling of emergency situations.

3.2 Displays

There are countless every day situations where visual displays are used, such as; entertainment systems, driving of cars, advertising media, medical and office applications. The development of new display technologies is driven by those fields where sales are highest, generally the computer and entertainment businesses. With the possible exception of very specialist military applications, the drivers will not change and the main challenge for aviation will be to apply effectively or adapt new technologies developed mainly for the consumer market.

Dedicated displays will disappear and the type of picture presented at any given time will be determined by the aircraft systems themselves, unless directly overridden by the user. New display media will open up new possibilities. Fully closed cockpits where the crew have no direct view of the outside world will be available. This opens the possibility of military aircraft where the occupants are protected from laser, light or electromagnetic radiations and hypersonic aircraft where no protrusion in the nose shape is required to give direct view for take off and landing. The display surfaces will initially be back projection displays where projectors above the pilots' feet illuminate the 'instrument panel' from behind. Multiple projectors will be used to protect against loss of display. However this type of display will be supplanted by light emitting displays formed directly on the inside surface of the cockpit. The ultimate flexibility will come with an enclosure material that can switch from transparent to opaque as an electric field is applied while continuing to emit a display on its inner surface. The opacity to the visible and electromagnetic spectrums will protect crews and their equipment from hostile radiations while the emitters continue to display the battlefield situation. When the threats have passed the enclosure returns to transparency and the crew resume direct observation of the outside world. On the ground we can envisage airfield controllers sat in entirely closed rooms but with a display of the airfield and its traffic surrounding them. Not only will every controller have an unobstructed view, but the need for major tower structures on the airfield or carrier deck will be avoided. Operators of UAVs will expect similar displays in their command cabins.

A major advance, colloquially known as synthetic vision, will use data from low light television, infra red and millimetric radars to produce a picture of a landing runway or military target even in the most adverse weather. Highly accurate navigation systems will ensure that the synthetic picture of the outside world accurately overlays the real outside world. An on board data base storing the geometry of the visible features in the area allows an even clearer image to be generated. This type of application offers huge advances in take off, approach and landing safety, particularly in parts of the world with poor navigation or airfield facilities. Existing synthetic vision applications use a head up display to project the image ahead of the user. Soon it will become common to project such images directly onto the retina of the eye using a helmet, headset or spectacle mounted projector.

Where a display is used to project an image that relates to the outside world, for instance to designate a target or to aim towards a runway, the picture must accurately register with the outside world. In order to do this it is necessary to know in which direction the user is looking, perhaps using a magnetic sensor on his helmet or headset. The mounting of the display projector on his headset, helmet or spectacles brings the advantage that the display moves with the user's head. Eye tracking devices will give even more accurate tracking of where the user is looking. Electronic display and sensor designs will become so light that such helmet or headset mounted devices will become light and cheap enough to be in every day use. Maintenance users will use the same devices to both receive guidance from a company's maintenance system and to relay pictures and images from first line back to the experts at base.

Holographic and '3D' displays will become available first in the military field. They will provide the combat crew with the ability to obtain better appreciations of a tactical situation. In civil aircraft they will provide the crew with a better perception of the aircraft's position relative to other traffic or to a descent or landing path.

3.3 The system design process

The manufacturing cost, weight and other features of the electronic components that carry out the computing elements of system functions are already so low that they do not figure strongly when we design new aircraft or systems and this trend shows no sign of ceasing. However design costs continue to rise. The limitations on the system functions provided in the future are likely to be:

- The ability to imagine what functions are needed.
- The ability to define them clearly and accurately.
- The cost of the systems and software design and certification processes.
- The costs of providing changed or upgraded functions particularly as airframe lives extend.

The most challenging of these are the ability to define accurately system functional requirements and the ability to verify and certify economically that the functions have been correctly implemented. The verification and certification processes will become even more closely embedded in the design process in order to verify the design progressively and thereby minimise major re-work of the design and save effort by avoiding duplication.

Currently the process of defining new functions is hampered by the human thought process. Usually the designer is good at thinking about what actions are required of a new function. It is only later that the unwanted interactions emerge and the specification of what shall not happen gets fully considered. The designer then tries out the ideas on potential system operators using everyday English or other language to communicate. Colloquial language is notoriously imprecise and misunderstandings creep in. This process will change. Tomorrow's designer will use a work station to enter his needs or requirements which will be held in a machine readable language. The work station will construct simulations and test scenarios and will present a representation of how the newly defined function would operate. The scenario generators will ensure that unexpected and system failure situations are evaluated in order to seek out unwanted interactions. The simulation and the scenario will be passed to the future users who will operate or 'fly' the simulation to confirm where it does and does not satisfy their needs. Designer, user and all others in the process will thus agree on a non ambiguous specification for the function. This model will then be translated into hardware and software designs which will be verified automatically.

If a system is to have flexibility for future change, this must be designed in from the outset. It is not sufficient to provide spare computing and interface capacity. If wholesale rewriting of software is to be avoided the overall structure of the software must be designed with change in mind. The future designer's workstation will pose questions to identify the type of future changes to be accommodated:

- Extra inputs and outputs (sensors, actuators and displays).
- What kind of function (e.g. maintenance, weapon aim, navigation).
- What other functions it might interact with.
- The degree of fault tolerance needed.

This data will be used to model and plan the partitions between the system functions and to allocate partitions for the functions to be added at a later date. The rigorous definition of partitions will ensure that the interactions with the existing software will be both minimised and accurately identified. This map of the software structure is the means of controlling the introduction of new functions. Certification of the changed function will then be confined to validation of the new functions themselves (unless they are imported from an already validated source) and the testing of the new interfaces that are being exercised. The locations and timing of the pre-existing functions will remain unchanged.

At one time the need to get maximum performance from primitive processors meant that expert programmers wrote programmes closely adapted to the internal structure of the processor itself. Growing and cheap processing power means that automatic tools to generate software from machine readable specifications will become common. The acceptance of the software the tools generate can either be by inspection and testing of the code they produce or by pre-verifying the dependability of the tools themselves. This latter task, verifying the accuracy of a suite of software generation tools, to a high degree of certainty, is huge and will be expensive. However, the tools are likely to be shared with other industries and the aviation industry's share of the total will be affordable. The advent of such a set of tools will also herald the application to Air Traffic Management Systems of the same processes for design and validation as used for flight software.

It will be feasible to send updated software to aircraft by data link. While this may have some military application such practice will be limited by the need to provide security to avoid hacking and the need to train the users in the new function. Obsolescent software developed to outdated standards will still be in use and require maintenance. Human ingenuity, with the accompanying expense, will provide the only means of resolving such problems.

3.4 Data and communication links

The basic flight control systems of aircraft use on board sensors to measure aircraft motion and subsequently to stabilise the craft. Data and communication links open up access to wider sources of information and stored data, such as radar identities of aircraft or targets, thus widening the amount of information that can be used for control and display. The number of entities to be linked can be large, including reconnaissance and coordination information from other aircraft, command and air traffic control data calculated by ground based computers and data flows from an aircraft to the weapons it is releasing. The vulnerable points in such distributed systems are the communication links, these being the obvious points to attempt to intercept or corrupt.

Satellites have freed data links from the limitation of line of sight radio links. It may be assumed that within the next twenty years near infinite capacity will be available between any two points on or close to the globe. While this enables huge benefit to the civilian world, in the military sphere each transmitter of data potentially gives away the location of a valuable asset, whether satellite, aircraft, weapon, or ground installation. In order to reduce vulnerability to detection and interception, growing use will be made of frequency agility and spread spectrum techniques, narrow angle electronically steerable antennae and narrow band laser communications.

The use of terrain matching techniques to navigate weapons or aircraft involves transmitting radio pulses to determine distance to the ground. Imaging by radar depends on transmitting high power pulses. The advanced development of low noise electronic receivers and powerful digital signal processing computers opens the possibility of making these measurements or seeing these images without radiating any radio energy. The background radio noise in the area will provide the illumination of the targets and the terrain.

An alternative to using sensors to gather information is to use calculated information. Already flight management systems use performance data bases to enable thrust, drag and other quantities to be accurately predicted.

The amount of paper on the flight deck will fall to zero being replaced by on board data bases containing fixed data, for example check lists, as well as variable data such as the load sheet or technical log. These on board data bases will be updated by data link when the aircraft is located in friendly environments and will ensure that the flight deck will always be up to date.

The passenger on a civil or military transport will have access to the same data facilities as at home or in his office. The limitations are likely to be imposed by finding the space for him to work rather than the ability to provide the information. It remains to be seen to what extent the traveller will appreciate being so easily contactable.

The downlink of data from the aircraft will be a vital part of the air traffic system. Additionally, by transmitting aircraft and system status to ground systems, enormous opportunities will be opened to provide rich data sources for post incident or post accident analysis and even flight operations quality assurance.

When the aircraft lands at a suitably equipped airfield, the software update status of all electronic devices will be polled while at the gate and, if appropriate, updated. Notification of the update will be given to the operating and maintaining crews. Vehicle health data collected in flight, passenger lists, food and beverage stocks and performance data will all be automatically exchanged and routed to the operator's information technology infrastructure with minimal human intervention.

3.5 Computing and control systems

As for display devices, advances in the capability of computers and sensors are most likely to be driven by the huge research and development budgets of the consumer world. Processing power that is cheaper in terms of power consumption, prime cost, weight and volume means that multi channel computation will be applied to a wide range of applications. It will be feasible to construct functions with more control channels than are strictly needed to provide the necessary reliability and integrity for a single flight or group of flights. The system will manage this spare capacity to perform self repair following failure and report the new system status together with the remaining reserve capacity to the on board maintenance system. This capability will extend to mechanical failures where the control system will adapt to a degraded function or 'get home' mode of operation.

Powerful computers coupled to on board sensors will enable see and avoid manoeuvres, target identification and selection and mission planning functions to be carried out on the aircraft. These can be offered to the crew for confirmation before action or in the case of uninhabited aircraft can be used directly for control. The greater sensing and control capabilities will provide accurate automatic control of take off, abort and landing even on primitive fields. The configuration/shape of a new generation of unconventionally shaped aircraft will be controlled by the avionic systems and new high efficiency power plants will depend on electronic control systems to operate at high efficiency. Dynamic load management systems will use accelerometers embedded in the airframe and auxiliary control surfaces to provide structural damping of large aircraft and to reduce airframe loadings from turbulence. No doubt passengers will enjoy the smoother ride and operating costs will be reduced as a result of the longer fatigue lives. The crew's position as high level system managers will be reinforced by placing the management of a plethora of functions, from energy distribution, through undercarriage control to cabin lighting, under the control of an extensive system managing the utility or infrastructure services of the aircraft.

The day of computers dedicated to specific tasks will be past. Sharing of computing in Integrated Modular Avionic systems (IMA) will bring economy while providing greater availability and reliability. The reliability of the electronic elements will be increased by reducing the number of electrical connections. Interconnection will be by fibre optic data bus where the operating environment is hostile and elsewhere by short range spread spectrum radio link, even within the computing centres themselves. Cameras operating in the Infra Red and Visible spectra will provide the ability to detect potential fires, find stowaways and allow the flight or maintenance crews to inspect the inside and outside of the structure for damage, ice or other pollutant.

3.6 Mission and flight management

All of the functions of mission and flight management will be greatly enhanced by the sensing, computing and display advances described above. In functional terms the greatest benefit will come from the certain knowledge of the aircraft's location and status and the knowledge of the runways, terrain, weather and traffic adjacent to the present location. This knowledge addresses the causes of a high percentage of hull losses and will provide a major contribution to increased safety of operation.

A new flight/mission management function will become commonplace. Under the generic name of 'Pilot Associate' it will collect data from the main avionic systems to perform status monitoring of the aircraft and its situation. Rather than provide another redundant control channel it will act as an independent observer to draw attention to unusual states or reduced separation margins. The situation may have been precipitated by system fault, crew action or inaction or by a conflicting aircraft. Situations detected will include systems failures, impending stall or descent into rotor downwash, unusually high apparent drag or fuel consumption, route conflicting with a storm ahead and approach of threatening aircraft. It will alert the user and bring into view the cockpit displays that exhibit the situation together with a check list of recommended actions. Should the crew choose to take different action, rather than repeat the previous advice it will revise its advice to take account of the action actually taken by the crew.

3.7 Air traffic management

The greatest inhibitor to increasing traffic density is the flight crew's lack of precise information on the longitudinal separation to the aircraft ahead or behind and of their neighbours' speed strategy. Control currently passes through a voice communication system, via the ground, with inherently large decision and communication delays. The large time delays, of the order of tens of seconds, mean that longitudinal separations can only be managed through a very slack control loop implying separations measured in miles. The future resolution of the airborne dilemma will be by providing up to date data on speed and direction intentions of the adjacent traffic and putting short term responsibility for separation with the flight management systems of each aircraft. This will allow longitudinal separations to fall by more than an order of magnitude. Most of the flight elements of the technology needed to do this already exist. The task of transitioning to such a new system will be dominated by the need to generate new, internationally accepted, operating procedures and computing systems for the ground elements.

High density operation such as this only becomes feasible if the ground systems have an order of magnitude greater dependability than the individual air vehicles' systems. This means that the ground part of the air traffic management system will be based on redundant/fault tolerant computing and certificated software.

Where there is sufficient airspace to allow traditional separations, individual aircraft will negotiate direct routings to their destinations through airborne to ground computer data links and free flight will flourish. Technically feasible, but probably rare outside low population parts of the world, will be the autonomous operation of private aircraft using satellite based navigation and on board ground and collision avoidance algorithms to shepherd low skill pilots to their destinations in all weathers.

In the terminal areas congestion and concentration of noise nuisance will be alleviated by varying the approach path for each succeeding aircraft. The airborne part of this capability is already available in many Western transports.

3.8 System health diagnosis

There will be major increases in the use of and reliance upon, 'health' and 'usage' systems and equipment on both civil and military aircraft. New sensor technologies and better data links will enable wider diagnostic capabilities. These will include:

- Increased use of and reliance upon, the monitoring of safety critical components such as engines and gearboxes, flying controls and flight instrumentation.
- Monitoring by embedded strain gauges, of critical structural components.
- Comparison of the structural vibration modes of the aircraft with stored models to give early identification of reduction in structural integrity.
- Detection of potentially hazardous external environmental effects, such as natural and wake turbulence, thunderstorms, hail and icing, with automatic adjustment of the aircraft power, flight path and systems to compensate for dangerous effects.
- Use of external and internal sensors and cameras to monitor, detect and alert the flight crew to hazardous occurrences, including potential security situations.

3.9 Countering external threats

In spite of the best weather forecasting techniques the atmosphere still holds many threats for aircraft. It seems reasonable to predict that in a time span considerably less than 100 years we will have developed sensors able to measure air velocity and temperature many hundreds of metres ahead of an aircraft. They will focus on small groups of molecules and detect their motions with or without stimulation by radiation from the sensing aircraft. By scanning the sector ahead of the aircraft it will be possible to detect the average velocity of the air mass as well as to identify wake turbulence and micro bursts. This will enable the separation of departing aircraft to be assured by measurement and avoidance of the wakes themselves, achieving a far higher traffic density than allowable where procedural separation is used. Detection and characterisation of micro bursts will greatly enhance safety of operation. En route the detection and management of wind and temperature shears will, at the minimum, give smoother travel and for high speed aircraft will lessen the occurrence of speed excursions.

One of the un-resolved threats to aircraft has been icing. There are many ways to detect icing conditions and avoidance of these conditions will be the preferred strategy for some vehicles. The detection of ice on the airframe or engine parts will more reliably be detected by observing the change in vibration modes of blades and aerofoil structures by vibration analysis (health diagnosis, above). Ice removal will continue to be an issue. The latent heat of ice is such that removal by melting will always be expensive in terms of energy as well as adding unwelcome heat to the structure. Chemical solutions are expensive, of mixed effectiveness and imply weight penalties. The remaining prospect is to exploit the brittle nature of ice by using impact methods to remove it. Such impacts also affect the structure and again, effectiveness varies according to ice thickness. There is currently extensive research and evaluation of methods to remove ice accretions. Whichever method is chosen, initiation and control of the process will almost certainly fall to the avionic systems.

External particle radiation will threaten the electronics of high flying aircraft. It is fortunate that the reducing size of semiconductor cells reduces the probability of an individual circuit being hit by a particle but this is more than offset by the reducing levels of electrical energy in the cell. With growing amounts of electronics in the aircraft, countering actions will be needed. This will involve the use of check sums and error detection and correction algorithms to ensure uninterrupted operation.

In military operation there will always be the threat of high energy pulses or continuous radiation to be countered. Closed cockpits (Section 3.2) will provide a solution where it is judged necessary to maintain manned operation. In other cases uninhabited air vehicles will prevail. Civil operations will be carried out in less demanding environments where the local use of electromagnetic screening and fibre optic interconnections will provide sufficient protection.

As other causes of aircraft loss are eliminated a growing fraction of losses will be due to failure to recover properly an otherwise sound aircraft from an unusual attitude or situation. Automatic recovery will become a feature of all flight guidance systems. Even though future air traffic control systems will be designed with high availability and reliability, aircraft will retain the ability to avoid collision with the ground or other craft in the event that the ground system closes down temporarily. Ground and collision avoidance will thus continue to be fitted.

The complexity of electronic or information warfare weapons will grow. New high power, high speed, electronic components will provide radar or countermeasures antennae that conform to the aircraft shape and use electronic switch elements to provide agile and multiple beams. High power dedicated computing will perform the convoluted tasks of providing false, distorted or cancelled returns to an enquiring enemy radar.

3.10 System of systems

We are moving rapidly into ‘end to end’ systems with, for example, the aircraft and all associated systems part of a total global infrastructure and capability.

In the military environment, the aircraft or the UAV is again just one of the players in the future ‘battle space’. Total intelligence and communication, normally by data links, will be provided for all the participants and the overall strategy implemented by optimising the tactics, on a continuing basis, as the local scenario changes and develops. Extensive precautions will be required to protect such an all-embracing system from corruption and infiltration.

On the civil side this integrated transport environment will mean that a simple telephone call or e-mail message requesting transportation from the caller’s given location to any other destination, on a required date, will be processed and made available as a complete logistics package. Thus the total inter-relationship between the various means of transport and the associated logistics will be complete with guaranteed availability and on time delivery. This may well be achieved by providing the passengers with a ‘podded’, containerised environment in which they travel throughout the whole journey. This environment would provide all the services required by the passengers for the total duration of the journey, including entertainment, food and all amenities. The boarding, security and immigration processes will be carried out on the passenger and baggage during the ground portion of the trip.

4.0 NEW CONCEPTS

System and avionic developments that depend on new physical, nuclear or chemical discoveries are the most difficult to foresee yet discoveries there will be. This section takes a less rigorous view of what might emerge and where these may possibly lead.

4.1 The man-machine interface

The most capable data port connecting the human brain to the outside world is the sense of vision. Perhaps information from the aircraft systems will be connected directly to the optic nerve. Perhaps even greater data transfers will take place by induced electrical connection direct to the nervous system. While such techniques increase the flow of data to the brain the end result could be that the operator’s brain becomes the limiting point in overall system performance. Perhaps it might be better to use the human brain to work on strategy and tactics, leaving second by second control to the less intelligent but more predictable automatic systems.

4.2 A new way to fly

Early in the second century of flight it will be possible to provide a flight control system that enables an unskilled person to control even a vertical take off vehicle through take off, transition to wing borne flight and back to a vertical landing. If designed for this unskilled operator, the system would certainly not have throttle, stick, rudder and collective controls. Its control stick would probably command fore & aft and vertical & lateral accelerations. There would be no flap or undercarriage lever; no throttle. Aircraft attitude would not be controlled directly. A five year old would probably manage such a control system intuitively and with accuracy. While our existing adult mind sets are not yet ready for such a change, the benefits in reduced training cost are so great that it will inevitably be adopted before the end of the next century. Where the vehicle lift is generated by rotor the individual blades will be each controlled separately ensuring mechanical and aerodynamic balance.

Associated with this capability will be the ability of the system to identify individual human operators and adjust the system performance to match the operator’s capabilities.

4.3 Greater trust in the automatics

In two major areas progress depends on the willingness of the human operator to trust his electronic systems. The first is a gradual and progressive delegation of both strategic and tactical control to the avionics with flight crew reducing to firstly a single flight licensed member and ultimately to the removal of all conventionally qualified flight crew. Even in this latter case a ‘Vehicle Manager’ or other representative will probably still be needed on board a civil aircraft to give confidence to the aircraft’s passengers. The second, and slightly more distant approach, is of increasing intelligence in the equipment itself comparable with, and perhaps exceeding, that of the human operator.

4.4 The machine that thinks for itself

By mid century there will be light, rugged computers with computing power massively exceeding that of the human brain, with sensors and data transmission to match. Computer programmes to harness this capability will be inordinately complex to specify, implement and test. Perhaps we will move to a process where the designer of a new system would specify the objectives for that system and a compiling computer would search the range of knowledge and experience accumulated to determine the operating programme to be embedded in the avionic computer. This programme would include thinking algorithms. To a mere human the avionic system behaviour would appear to be intelligent rather than deterministic. The authorities responsible for transport regulation would also have their own compiling computer which would identify the precautions or tests to be undertaken before the new avionic system were let loose on the public.

4.5 Energy sources and distribution

As an aircraft travels on its journey, most of the energy consumed is dissipated in heating the atmosphere. For higher altitude aircraft the sun provides a continuous energy flux, at present generally unused. The next century could see a new thermodynamic transducer that exploits the temperature difference between the heated skin and immediately surrounding atmosphere of hypersonic vehicles and the low temperatures of the adjacent atmosphere to recover energy into the aircraft. Less radically, high altitude loitering vehicles will benefit from low weight, high efficiency, solar cells to collect and store energy.

Another means to transfer power to the aircraft could be using power beams or rays. There already is experimental use of chemically stimulated lasers to send energy in a focussed beam through the atmosphere. If the energy density is high enough the beam does not become de-focussed by the air and much of the energy arrives at the destination. There are also proposals to send radio frequency energy, generally not subject to attenuation by the atmosphere, in a narrow beam to provide energy to power light weight ‘aerostats’. Other than in war situations it seems unlikely that such mechanisms will enter everyday use. They depend on line of sight positioning of transmitter and receiver and any third party crossing the beam would cut off the flow of energy, and if the flux were high, be itself damaged or destroyed.

The development of hydrogen based fuel cells and ‘clean’ nuclear power sources would have a major effect upon the availability and usage of power in future aircraft, possibly leading to the use of plasma propulsion for very high altitude vehicles.

In addition to the power needed for propulsion, large amounts of energy are needed to provide the aircraft services. Energy is currently stored in hydraulic accumulators and electrical batteries for use in emergencies or to start up in remote locations. This energy storage and distribution system adds weight, volume and has its own repair and maintenance costs. We need better ways to transfer and store energy. Ideally we would like a new physical mechanism that sends a flux of energy throughout the aircraft structure itself to all potential users without adding weight.

4.6 Future aircraft

The advent of commercial space travel, both to global and outer space destinations, will doubtless take place within the next century. Their success will be dependant upon the availability of appropriate systems for control and all other services. Within the constraints of safety and cost, such systems and equipment will be designed and developed, with perhaps the future emphasis being on creating and sustaining an acceptable environment, under extreme conditions, for the occupants. This may involve more monitoring and control of the body functions by the vehicle systems.

Future military needs, real or perceived, will also be reliant upon the vehicle systems to satisfy these demands.

4.7 Or no aircraft?

In 1903, transportation included the horse and wagon, steam trains, steam ships, and a new oddity called an automobile. The ability of man to fly was limited to balloons. Who would have believed by the end of the century steam would be replaced almost completely by electricity for trains and ships; the horse and wagon would give way to diesel trucks and man would routinely get into a large aluminium tube and fly from one city to another? Is a similar revolution looming?

Artificial environments will be commonplace within the next century. These rooms or cocoons will virtually transport the human occupant anywhere in the world through sophisticated aural, visual, olfactory and tactile nano-engineered sensors and machines. As a result of the green revolution and the non-availability of hydrocarbon fuels, people may see less need to travel and human interaction may become limited to those people in one’s immediate community. Business would routinely be conducted from these environments and manufacturing take place in factories without humans, under the control of specially designed machines and computers.

Before the end of the century, the tele-transporter would become a reality for those who do want to travel and they would simply book their time slot, step into the machine and be painlessly, electronically deconstructed at the departure point and reconstructed at the destination. For high value goods, the molecular definition would be transmitted to the destination where the same process would construct the product. Lower value goods would be transported in large uninhabited transport aircraft to avoid the costs of the energy used in the reconstruction process.

5.0 CONCLUSIONS AND ACKNOWLEDGEMENTS

The growing adoption of the holistic or systems approach to problem solving and design and the investments being made in advancing computing technology mean that systems and avionics will be central to the aeronautics of the next century. There will be many surprises in store, many of which will not have been foreseen.

It is difficult to break the bonds of today’s conventions and imagine a wholly new future. We are grateful for the encouragement, stimulus and ideas from our colleagues in the systems and avionics industry. Thanks are particularly due to Frank Daly of Honeywell, Jerry Haller of Smiths, Brian Wright of Collins, Brian Tucker of BAE System and their staffs.